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14 The Behavior of Gases

Big idea KINETIC THEORY

14.1 Properties of Gases

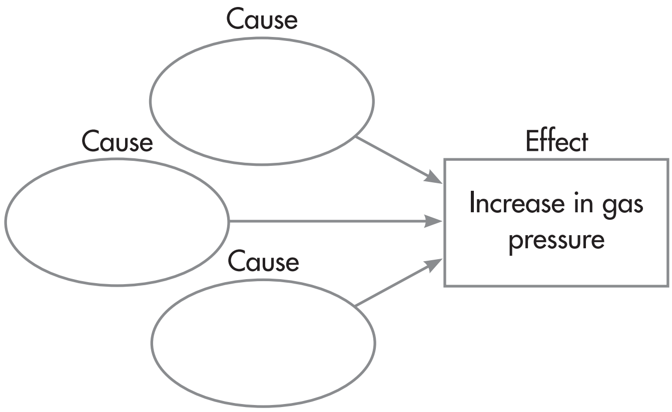
For students using the Foundation edition, assign problems: 2–5, 7–9, 11, 12–15.

Essential Understanding Kinetic theory is an attempt to explain some of the properties of gases by describing how particles interact with one another.

Reading Strategy

Cause and Effect Identifying cause and effect can help you understand the relationship among events. A cause is the reason something happens. The effect is what happens. In science, many actions cause other actions to happen.

As you read Lesson 14.1, use the cause and effect chart below. Record three causes for an increase in gas pressure.



EXTENSION Below each cause, use kinetic theory to explain how it will increase the gas pressure.

Lesson Summary

Compressibility Gases can expand to fill its volume, and gases can be squeezed into a smaller volume.

- Gases do not have definite shape or volume.
- Gases are easily compressed because of the space between molecules in a gas.

Factors Affecting Gas Pressure Gases exert pressure.

- Collisions between molecules of gases and the walls of its container cause the pressure in a closed container of gas.
- Factors that affect the gas pressure *(P)* of an enclosed gas are its temperature *(T)*, its volume *(V)*, and the number of molecules.

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Effect of factor on gas pressure	(*T*)	(*V*)	Number of molecules	(*P*)
Increasing (*T*) will increase (*P*) if (*V*) and number of molecules are constant.	↑	constant	constant	↑
Decreasing (*V*) will increase (*P*) if (*T*) and number of molecules are constant.	constant	↓	constant	↑
Increasing the number of molecules will increase (*P*) if (*V*) and (*T*) are constant.	constant	constant	↑	↑

After reading Lesson 14.1, answer the following questions.

Compressibility

1. Look at Figure 14.1. Explain how an automobile air bag protects the people in the car from being hurt as a result of impact.

The gases used to inflate the air bag are able to absorb a considerable amount of energy when they are compressed.

2. What theory explains the behavior of gases? ***kinetic theory***

3. Circle the letter next to each sentence that is true concerning the compressibility of gases.

(a.) The large relative distances between particles in a gas means that there is considerable empty space between the particles.

(b.) The assumption that particles in a gas are relatively far apart explains gas compressibility.

(c.) Compressibility is a measure of how much the volume of matter decreases under pressure.

d. Energy is released by a gas when it is compressed.

Factors Affecting Gas Pressure

4. List the name, the symbol, and a common unit for the four variables that are generally used to describe the characteristics of a gas.

a. ***pressure, P, kilopascals***

b. ***volume, V, liters***

c. ***temperature, T, kelvins***

d. ***amount of gas, n, moles***

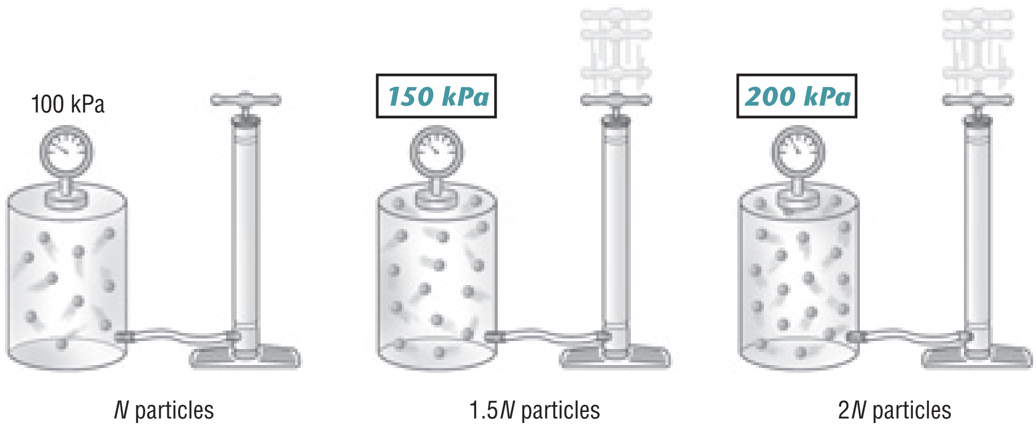
5. What keeps the raft in Figure 14.3 inflated?

The air pressure exerted by the enclosed gas keeps a raft inflated.

6. How do conditions change inside a rigid container when you use a pump to add gas to the container?

Because particles are added to the container, the pressure increases inside the container.

7. The diagrams below show a sealed container at three pressures. Complete the labels showing the gas pressure in each container.



8. What can happen if too much gas is pumped into a sealed, rigid container?

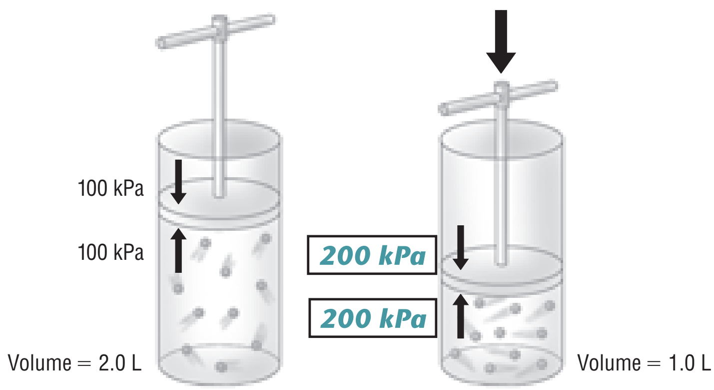
The pressure inside the container can increase beyond the strength of its walls, causing the container to rupture or burst.

9. Is the following sentence true or false? When a sealed container of gas is opened, gas will flow from the region of lower pressure to the region of higher pressure. ***false***

10. Look at Figure 14.5. What happens when the push button on an aerosol spray can is pressed?

Pushing the button creates an opening between the atmosphere and the gas inside the can, which is at a higher pressure. Gas from inside the can rushes out of the opening, forcing the product in the can out with it.

11. In the diagram, complete the labels showing the pressure on the piston and the gas pressure inside the container.



12. When the volume of a gas is reduced by one half, what happens to its pressure?

The pressure will double.

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13. Is the following sentence true or false? Raising the temperature of a contained gas causes its pressure to decrease. ***false***

14. Circle the letter next to each sentence that correctly describes how gases behave when the temperature increases.

   (a.) The average kinetic energy of the particles in the gas increases as the particles absorb energy.

   (b.) Faster-moving particles impact the walls of their container with more force, exerting greater pressure.

   c. When the average kinetic energy of the enclosed particles doubles, temperature doubles and the pressure is cut in half.

15. Explain why it is dangerous to throw aerosol cans into a fire.

   Throwing an aerosol can into a fire causes the gas pressure inside the can to increase greatly, with the likelihood that the can will burst.

16. Decide whether the following sentence is true or false, and explain your reasoning. When the temperature of a sample of steam increases from 100°C to 200°C, the average kinetic energy of its particles doubles.

   False. For average kinetic energy to double, the temperature must increase from 100°C (373 K) to 473°C (746 K).

14.2 The Gas Laws

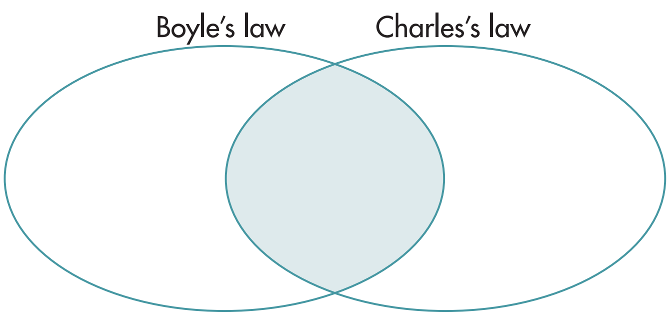
For students using the Foundation edition, assign problems: 1–9, 11–19.

Essential Understanding The gas laws are a set of mathematical tools to help predict the behavior of gases under specific conditions of pressure *(P)*, temperature *(T)*, volume *(V)*, and number of moles of gas *(n)*.

Reading Strategy

Compare and Contrast A Venn diagram is a useful tool in visually organizing related information. A Venn diagram shows which characteristics the concepts share and which characteristics are unique to each concept.

As you read Lesson 14.2, use the Venn diagram to compare Boyle's law and Charles's law.



EXTENSION Use a three-circle Venn diagram to compare Boyle's law, Charles's law, and the combined gas law.

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Lesson Summary

Boyle's Law: Pressure and Volume Boyle's law states that the pressure and volume of a gas are inversely proportional to each other (constant *T*, *n*).

- The equation for Boyle's law is $P_1 \times V_1 = P_2 \times V_2$

Charles's Law: Temperature and Volume Charles's law states that the volume of a gas is directly proportional to its Kelvin temperature (constant *P*, *n*).

- The equation for Charles's law is $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

Gay-Lussac's Law: Pressure and Temperature Gay-Lussac's law states that the pressure of a gas is directly proportional to its Kelvin temperature (constant *V*, *n*).

- The equation for Gay-Lussac's law is $\frac{P_1}{T_1} = \frac{P_2}{T_2}$

The Combined Gas Law The combined gas law describes the relationship among the pressure, volume, and Kelvin temperature of a gas (constant *n*).

- The equation for the combined gas law is $\frac{P_1 \times V_1}{T_1} = \frac{P_2 \times V_2}{T_2}$

Gas law	(*T*)	(*V*)	(*n*)	(*P*)
Boyle's law	constant	↓	constant	↑
Charles's law	↑	↑	constant	constant
Gay-Lussac's law	↑	constant	constant	↑

BUILD Math Skills

Isolating a Variable Remember that all equations have two sides—a left side and a right side. The first step in isolating a variable is to get any term with the variable in it on one side of the equation. The next step is to get rid of everything else on the same side of the equation as the variable.

In order to get rid of the 'extra' variables, you must undo its association with that side of the equation. To do this, you do the opposite operation to both sides.

Turn to the next page to learn more about isolating a variable.

Sample Problem Solve for x in $x + 2 = 14$.

The key to solving this equation is to isolate *x*.

$$x + 2 = 14$$

Hint: It is important that you subtract 2 from both sides, otherwise you can't use an equals sign.

On the left side of the equation, *x* is added to 2. To undo addition, you must subtract 2 from both sides of the equation.

$$(x + 2) - 2 = 14 - 2$$
$$x = 12$$

Sample Problem Isolate V_1 in the equation: $\frac{V_1}{T_1} = \frac{V_2}{T_2}$

You need to get V_1 by itself on the left side. So you need to move T_1 to the right side.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

To undo the division of V_1 by T_1, you just multiply both sides by T_1.

$$\frac{\cancel{T_1}}{} \times \frac{V_1}{\cancel{T_1}} = \frac{V_2 \times T_1}{T_2} \text{ so } V_1 = \frac{V_2 \times T_1}{T_2}$$

Isolate the variables in the problems below.

1. Isolate V_2 in the equation: $\frac{V_1}{T_1} = \frac{V_2}{T_2}$ $V_2 = \frac{V_1 \times T_2}{T_1}$

2. Isolate T_2 in the equation: $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ $T_2 = \frac{T_1 \times P_2}{P_1}$

3. Isolate P_2 in the equation: $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ $P_2 = \frac{T_2 \times P_1}{T_1}$

After reading Lesson 14.2, answer the following questions.

Boyle's Law: Pressure and Volume

4. Circle the letter of each sentence that is true about the relationship between the volume and the pressure of a contained gas at constant temperature?

- **(a.)** When the pressure increases, the volume decreases.
- **(b.)** When the pressure decreases, the volume increases.
- **c.** When the pressure increases, the volume increases.
- **d.** When the pressure decreases, the volume decreases.

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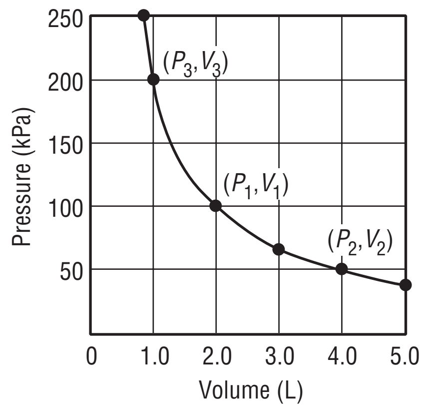
5. ***Boyle's*** law states that for a given mass of gas at constant temperature, the volume of the gas varies inversely with pressure.

Questions 6, 7, 8, and 9 refer to the graph. This graph represents the relationship between pressure and volume for a sample of gas in a container at a constant temperature.



6. $P_1 \times V_1$ = ***100 kPa × 2.0 L***

7. $P_2 \times V_2$ = ***50 kPa × 4.0 L***

8. $P_3 \times V_3$ = ***200 kPa × 1.0 L***

9. What do you notice about the product of pressure times volume at constant temperature?

Pressure times volume is constant.

Charles's Law: Temperature and Volume

10. Look at the graph in Figure 14.10. What two observations did Jacques Charles make about the behavior of gases from similar data?

The graph for volume versus temperature of any gas is a straight line, and the line always intersects the temperature axis at the same point, –273.15°C.

11. What does it mean to say that two variables are directly proportional?

When one variable increases, the other increases so that the ratio of the two variables remains constant.

12. Is the following sentence true or false? Charles's law states that when the pressure of a fixed mass of gas is held constant, the volume of the gas is directly proportional to its Kelvin temperature. ***true***

13. Charles's law may be written $\frac{V_1}{T_1} = \frac{V_2}{T_2}$ at constant pressure if the temperatures are measured on what scale? ***the Kelvin scale***

Gay-Lussac's Law: Pressure and Temperature

14. Complete the following sentence. Gay-Lussac's law states that the pressure of a gas is ***directly proportional to the Kelvin temperature if volume is constant.***

15. Gay-Lussac's law may be written $\frac{P_1}{T_1} = \frac{P_2}{T_2}$ if the volume is constant and if the temperatures are measured on what scale? ***the Kelvin scale***

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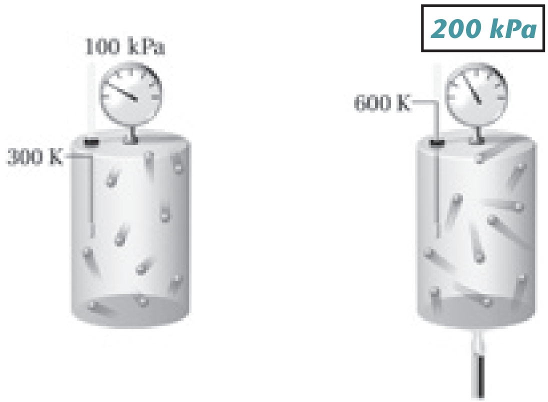
16. Complete the missing label in the diagram below showing the pressure change when a gas is heated at constant volume.



The Combined Gas Law

17. Is the following sentence true or false? The gas laws of Boyle, Charles, and Gay-Lussac can be combined into a single mathematical expression. ***true***

Questions 18–21 refer to the following equation:

$$\frac{P_1 \times V_1}{T_1} = \frac{P_2 \times V_2}{T_2}$$

18. What law does this mathematical equation represent?

the combined gas law

19. Which gas law does this equation represent if temperature is held constant so that $T_1 = T_2$? ***Boyle's law***

20. Which gas law does this equation represent if pressure is held constant so that $P_1 = P_2$?

Charles's law

21. Which gas law does this equation represent if volume is held constant so that $V_1 = V_2$?

Gay-Lussac's law

22. In which situations does the combined gas law enable you to do calculations when the other gas laws do not apply?

The combined gas law allows calculations for situations where none of the variables—pressure, temperature, or volume—are constant.

14.3 Ideal Gases

For students using the Foundation edition, assign problems: 1–8, 10–11.

Essential Understanding The gas laws are combined into the ideal gas law, which mathematically relates the four gas variables.

Lesson Summary

Ideal Gas Law The combined gas law can be modified to include the number of moles, *n*.

▶ The ideal gas law is $PV = nRT$.

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Ideal Gases and Real Gases At many conditions of temperature and pressure, real gases behave like ideal gases.

- Real gas particles have volume and exert forces on each other.
- Real gases differ most from ideal gases at low temperatures and high pressures.

After reading Lesson 14.3, answer the following questions.

Ideal Gas Law

1. In addition to pressure, temperature, and volume, what fourth variable must be considered when analyzing the behavior of a gas?

The fourth variable is the amount of gas.

2. Is the number of moles in a sample of gas directly proportional or inversely proportional to the number of particles of gas in the sample?

directly proportional

3. At a specified temperature and pressure, is the number of moles of gas in a sample directly proportional or inversely proportional to the volume of the sample?

directly proportional

4. Circle the letter next to the correct description of how the combined gas law must be modified to introduce the number of moles.

a. Multiply each side of the equation by the number of moles.

b. Add the number of moles to each side of the equation.

c. Divide each side of the equation by the number of moles.

5. For what kind of gas is (P × V) / (T × n) a constant for all values of pressure, temperature, and volume under which the gas can exist? *an ideal gas*

6. What constant can you calculate when you know the volume occupied by one mole of gas at standard temperature and pressure? *R, the gas constant*

7. Use what you know about the ideal gas law to answer the question. What would be the units for *R* if *P* is in pascals, *T* is in Kelvins, *V* is in liters, and *n* is in moles?

L•Pa/(K•mol)

8. Complete the table about the ideal gas law. Write what each symbol in the ideal gas law represents, the unit in which it is measured, and the abbreviation of the unit.

Symbol	Quantity	Unit	Abbreviation for Unit
P	*pressure*	*kilopascals*	*kPa*
V	*volume*	*liters*	*L*
n	*amount of gas*	*moles*	*mol*
R	*gas constant*	*liters x kilopascals / kelvins x moles*	*L•kPa / K•mol*
T	*temperature*	*kelvins*	*K*

9. When would you use the ideal gas law instead of the combined gas law?

The ideal gas law lets you calculate the number of moles of gas at any specified values of P, V, and T.

Ideal Gases and Real Gases

10. Circle the letter of each sentence that is true about ideal gases and real gases.

a. An ideal gas does not follow the gas laws at all temperatures and pressures.

b. An ideal gas does not conform to the assumptions of the kinetic theory.

(c.) There is no real gas that conforms to the kinetic theory under all conditions of temperature and pressure.

(d.) At many conditions of temperature and pressure, real gases behave very much like ideal gases.

11. Is the following sentence true or false? If a gas were truly an ideal gas, it would be impossible to liquefy or solidify it by cooling or by applying pressure. ***true***

12. Real gases differ most from an ideal gas at ***low*** temperatures and ***high*** pressures.

13. Circle the letter(s) that complete the statement. Ideal gas particles

(a.) move randomly.

b. have no kinetic energy.

c. repel each other at high pressure.

(d.) have no mass.

14.4 Gases: Mixtures and Movements

For students using the Foundation edition, assign problems: 1–5.

Essential Understanding Gas pressure depends only on (1) the number of particles in a given volume and (2) their average kinetic energy. The kind of particle is not important.

Lesson Summary

Dalton's Law Dalton's law states that in a mixture of gases, the total pressure is the sum of the partial pressures of the component gases.

- Dalton's law is expressed as $P_{total} = P_1 + P_2 + P_3 \ldots$.

Graham's Law Gases of lower molar mass diffuse and effuse faster than gases of higher molar mass.

- The diffusion and effusion of a gas depends on the type of gas molecule.
- Graham's law states that the rates of effusion of two gases are inversely proportional to the square roots of their molar masses.
- To compare the rates of effusion of two gases use $\frac{\text{Rate}_A}{\text{Rate}_B} = \sqrt{\frac{\text{molar mass}_B}{\text{molar mass}_A}}$

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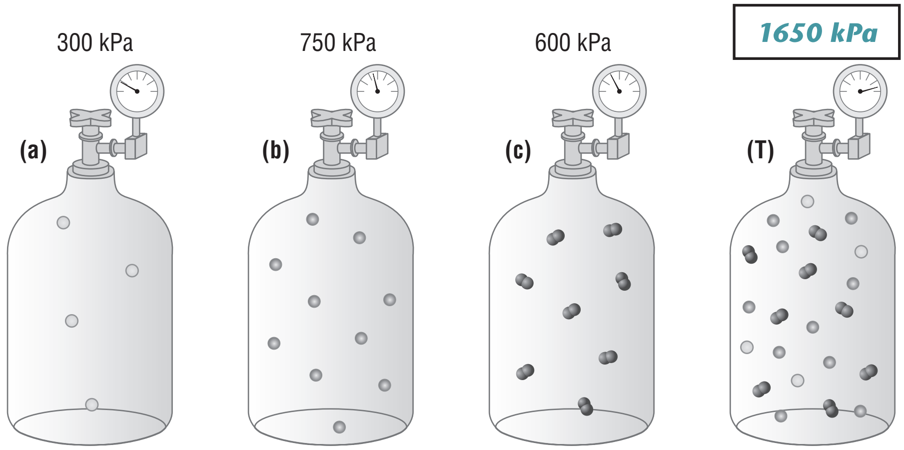
After reading Lesson 14.4, answer the following questions.

Dalton's Law

1. Is the following statement true or false? Gas pressure depends only on the number of particles in a given volume and on their average kinetic energy. The type of particle does not matter. ***true***

2. The contribution of the pressure of each gas in a mixture to the total pressure is called the ***partial pressure*** exerted by that gas.

3. Container (T) in the figure below contains a mixture of the three different gases in (a), (b), and (c) at the pressures shown. Write in the pressure in container (T).



4. Is the following sentence true or false? If two objects with different masses have the same kinetic energy, the one with the greater mass must move faster. ***false***

Graham's Law

5. What is Graham's law of effusion?

Graham's law of effusion states that the rate of effusion of a gas is inversely proportional to the square root of the gas's molar mass.

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Guided Practice Problems

Answer the following questions about Practice Problem 15.

A gas at 155 kPa and 25°C has an initial volume of 1.00 L. The pressure of the gas increases to 605 kPa as the temperature is raised to 125°C. What is the new volume?

Analyze

a. Temperature can be converted from Celsius to Kelvin by adding ***273***.

b. What is the expression for the combined gas law? $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$

c. What is the unknown in this problem? V_2

Calculate

d. Convert degrees Celsius to kelvins.

T_1 = 25°C + **273** = **298** K

T_2 = 125°C + **273** = **398** K

e. Rearrange the combined gas law to isolate V_2

$$V_2 = \frac{V_1 \times P_1 \times T_2}{P_2 \times T_1}$$

f. Substitute the known quantities into the equation and solve.

$$V_2 = \frac{1.00\ \text{L} \times 155\ \text{kPa} \times 398\ \text{K}}{605\ \text{kPa} \times 298\ \text{K}} = 0.342\ \text{L}$$

Evaluate

g. Explain why you think your answer is reasonable.

The new volume is directly proportional to the change in temperature but inversely proportional to the change in pressure. The temperature increased by a multiple of about $\frac{4}{3}$, but the inverse of the pressure change is $\frac{1}{4}$, giving a product of $\frac{1}{3}$. Therefore, the new volume should be about $\frac{1}{3}$ the original volume.

h. Are the units in your answer correct? How do you know?

Yes, because volume is measured in liters.

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Answer the following questions about Practice Problem 33.

Determine the total pressure of a gas mixture that contains oxygen, nitrogen, and helium if the partial pressures of the gases are as follows:

P_{O_2} = 20.0 kPa P_{N_2} = 46.7 kPa P_{He} = 26.7 kPa.

Analyze

a. What is the expression for Dalton's law of partial pressure? $P_{total} = P_1 + P_2 + P_3$

b. What is the unknown in this problem? P_{total}

Calculate

c. Substitute the known quantities into the equation and solve.

P_{total} = 20.0 kPa + 46.7 kPa + 26.7 kPa = 93.4 kPa

Evaluate

d. Why is your answer reasonable?

The total pressure can be estimated to be 20 + 50 + 25 = 95. The answer 93.4 is close to the estimate of 95.

Extra Practice

A gas has a pressure of 7.50 kPa at 420 K. What will the pressure be at 210 K if the volume does not change?

$$P_2 = \frac{7.50\text{ kPa} \times 210\text{ K}}{420\text{ K}} = 3.8\text{ kPa}$$

Apply the Big idea

A student analyzes a problem and lists the following knowns and unknowns.

KNOWNS	UNKNOWN
V_1 = 500 mL	V_2
T_1 = 25°C	
T_2 = 40°C	

He calculates V_2 and gets –80 mL. Is this value correct? Explain why or why not.

No, the volume can't be a negative value. The student forgot to change °C to kelvins.

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14 Self-Check Activity

For Questions 1–10, complete each statement by writing the correct word or words. If you need help, you can go online.

14.1 Properties of Gases

1. Gases are easily compressed because of the ***space between particles*** in a gas.

2. The amount of gas (*n*), volume (*V*), and temperature (*T*) are factors that affect ***gas pressure*** .

14.2 The Gas Laws

3. As the pressure of a gas increases, the ***volume*** decreases, if the temperature is constant.

4. As the ***temperature*** of an enclosed gas increases, the volume increases, if the pressure is constant.

5. As the temperature of an enclosed gas increases, the ***pressure*** increases, if the volume is constant.

6. The ***combined gas law*** allows you to do calculations for situations in which only the amount of gas is constant.

14.3 Ideal Gas Laws

7. Calculating the number of moles of a contained gas requires an expression that contains the variable ***n*** .

8. Real gases differ most from an ideal gas at ***low*** temperatures and ***high*** pressures.

14.4 Gases: Mixtures and Movements

9. In a mixture of gases, the total pressure is the sum of the ***partial pressures*** of the gases.

10. Gases of lower molar mass diffuse and effuse faster than gases of ***higher*** molar mass.

If You Have Trouble With...										
Question	1	2	3	4	5	6	7	8	9	10
See Page	413	414	418	420	422	424	426	428	432	435

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Review Key Equations

Read the answer and find the question that matches.

Answer

__*D*__ **1.** This equation $PV = nRT$ shows the relationship between a variety of gas properties.

__*B*__ **2.** This variable must remain constant for the combined gas law to be true.

__*E*__ **3.** Gay-Lussac's law relates these two gas variables.

__*A*__ **4.** This gas law relates volume and temperature.

__*F*__ **5.** This law allows you to compare the rates of effusion of two gases.

__*G*__ **6.** This gas law relates pressure and volume.

__*C*__ **7.** In Dalton's law, the partial pressures of the component gases are related to the total pressure by this function.

Question

A. What is Charles's law?

B. What is the number of moles?

C. What is the sum?

D. What is the ideal gas law?

E. What are the temperature and pressure?

F. What is Graham's law of effusion?

G. What is Boyle's law?

EXTENSION **As you choose the question, write the equation that identifies the gas law.**

Review Vocabulary

Choose a synonym from the list below for each of the four vocabulary words. Then come up with a way that will help you remember the meaning of the words. One has been done for you.

flow out | incomplete force | spread out | ability to give to pressure

Vocabulary	Synonym	How I'm Going to Remember the Meaning
compressibility	***ability to give to pressure***	ss in compress reminds me of the ss in pressure
partial pressure	***incomplete force***	
diffusion	***spread out***	
effusion	***flow out***	